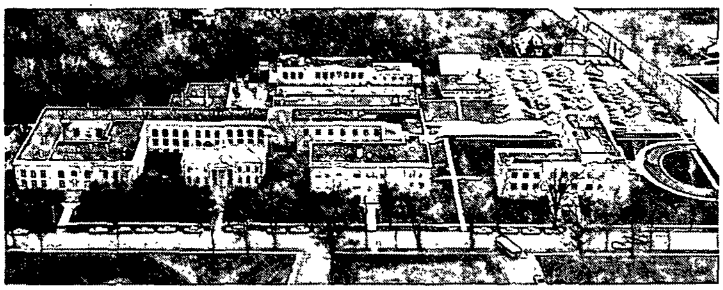
176



THE INSTITUTE OF PAPER CHEMISTRY, APPLETON, WISCONSIN

IPC TECHNICAL PAPER SERIES
NUMBER 176

NEW MECHANISMS IN WEB CONSOLIDATION

C. H. SPRAGUE AND S. W. BURTON

MAY, 1986

NEW MECHANISMS IN WEB CONSOLIDATION

C. H. Sprague
Director, Engineering Division
The Institute of Paper Chemistry
Appleton, Wisconsin 54912 U.S.A.

S. W. Burton
Ph.D. Candidate
The Institute of Paper Chemistry
Appleton, Wisconsin 54912 U.S.A.

ABSTRACT

Web consolidation processes and papermaking furnishes have evolved together to satisfy today's production and end-use performance requirements. Despite the harmony of this situation, these technologies do not develop the full potential of the furnishes now in use, and there are serious natural barriers to substantial improvements. Presses now operate near the practical and useful limits of pressure and time, and independent control of density and dryness is virtually impossible. Conventional drying technology is limited by low thermal driving forces, purely evaporative water removal, and partial pressure transport gradients. The influence of drying on paper properties is modest, at best. To achieve large gains in dewatering and property development performance, consolidation processes involving totally new driving forces or conventional driving forces of much higher intensity must be used. This paper describes a family of web consolidation processes based on such new or augmented driving forces. Emphasis is placed on the mechanisms by which these new forces promote dewatering and end-use property development and control.

INTRODUCTION

In conventional papermaking only a relatively small amount of water is removed by the pressing and drying processes. Despite their limited capacity for water removal, these processes have a large impact on paper machine operating costs and paper properties. Many new developments introduced over the past few years have improved the performance of the pressing and drying sections. These developments can be expected to continue to yield still further improvements. The additional gains are likely to be small, however, because of the fundamental limitations which bound the performance of current pressing and drying processes. Large improvements in performance will require the use of new or much more intense dewatering and densification forces. This paper considers two processes which embody such forces: displacement pressing and impulse drying.

WET PRESSING

The Conventional Pressing Process

In wet pressing, water is removed from a wet web by "squeezing" it between a plain roll or shoe (1) and a felt backed by a plain or vented roll. As the web is compressed, the network pore volume is progressively reduced and eventually becomes equal to the volume of the available water, a condition known as saturation. Further compression pressurizes the water, causing it to flow out of the sheet into the felt. As this process continues, compression of the fiber walls commences, causing water to flow from the fiber pores to the network pores and eventually out of the sheet. Rewetting may occur in the exit part of the nip as water flows from the felt back to the expanding paper web.

Time and pressure are the key variables in wet pressing (2). For sheets that are quite wet, heavy, or of high flow resistance, dewatering is flow controlled, and the product of average nip pressure and nip residence time, called the press impulse, determines overall water removal. Pressure and time may be freely interchanged in this regime to achieve a given level of dewatering. For sheets that are quite dry, light, or of low flow resistance, dewatering of fibers becomes the dominant process leading to compression control. In this regime, press impulse is still an important variable, but pressure now exhibits an important independent effect.

Current pressing technologies, including the extended nip press (3), produce press exit dryness levels generally in the 50% range, leaving about one gram of water per gram of fiber to be evaporated in the dryers. For each percentage point increase in this solids level, there is a corresponding 4.5% drop in dryer energy consumption. Web apparent density, a key factor in most strength properties, also increases almost linearly with press exit dryness up to 60% solids or so (4). Hence, dryer operating costs and paper properties would both benefit from higher press exit dryness, making this a prime target in pressing research.

With presses now operating near or at the limits of time and pressure, there is little that can be done within current technology to produce the dewatering force necessary to substantially increase press exit dryness. Studies have shown (5), however, that dryness levels of 70% or higher are potentially reachable by mechanical water removal. At these drying levels, however, it is difficult to saturate the network pores and produce a workable hydraulic pressure gradient. The low network permeability of a highly compressed web exacerbates the problem. Despite these barriers to mechanical water removal, there is still appreciable liquid water within the network that can be removed without thermal energy. Displacement pressing, a concept borrowed from the impulse drying process described below, brings into play a new driving force to effect partial removal of this additional water.

Displacement Pressing

In displacement pressing, a transverse compressive pressure sufficient to produce a saturated or near saturated state is employed. Water is then "displaced" from the web by imposing an external fluid pressure gradient, usually with compressed air. For webs that have already been well pressed by conventional means, displacement pressing is used to achieve still higher solids levels. For relatively wet webs, displacement pressing can be used to produce high dryness levels without reducing sheet bulk.

Figure 1 shows a schematic of a pressing head for laboratory study of displacement pressing. It includes a normal felt as a water receiver and load spreaders above the sheet and below the felt that permit uniform application of pressure to the sheet. The load spreaders are porous to allow air flow through the wet web. This head is installed in a falling-weight press simulator (6) or electrohydraulic press which provides the necessary web compression profile.

Simplified analysis. To gain understanding of the primary effects of web and operating parameters, a highly simplified analysis of displacement pressing has been performed. Because of the success of zonal models in describing high-intensity drying, a two-zone model has been adopted (see Fig. 2). In this model, the water available for displacement by an air pressure gradient is considered to be displaced from the web as a unit (wet zone), leaving behind (in the "dry" zone) that water which is unavailable for displacement. The analysis was performed for the general case in which air flows through the entire web removing water by viscous entrainment. However, the special case of a saturated wet zone, with water removal by a "push-through" mechanism, is readily handled in the model by setting the air permeability of the wet zone to zero.

As a result of mechanical compression, the web has a thickness (ℓ_T), an effective density of water available for displacement ($\overline{\rho_L}$), air permeabilities for the wet and "dry" zones (k_{a_w}, k_{a_d}), and a liquid permeability in the wet zone (k_L). The above quantities, as well as the applied air pressure difference (Δp_{a_o}), are considered constant. For simplicity, the compressibility of the air is neglected [i.e., the air density (ρ_a) is treated as constant]. It is assumed that Darcy's law adequately describes both the air and water flows. Although the wet zone thickness will decrease with time, a quasi-steady-state analysis is employed.

An analysis based on the above assumptions yields the following expression for the wet zone thickness as a fraction of the total thickness:

$$\frac{\delta}{\delta_T} = \frac{-\overline{k} + \sqrt{1 - (1-\overline{k}^2)\overline{t}}}{1 - \overline{k}}, \quad o < \overline{t} < 1 \tag{1}$$

where $\overline{k} = k_{a_w}/k_{a_d}$

$\overline{t} = t/tp$

$$tp = \text{"pressing time"} = \frac{(1+\overline{k})\mu_L m_L'' \delta_T}{2\,\rho_L\, k_L\, \Delta p_{a_o}} = \frac{(1+\overline{k})\mu_L\, \delta_T^2}{2\, k_L\, \Delta p_{a_o}} \tag{2}$$

$m_L'' = \rho_L \overline{\delta}_T$ = mass of water available for displacement per unit area

Of course, for $\overline{t} > 1$, no further water removal occurs, since $\delta = o$. The relative water removal (cumulative) is easily derived from the above result as:

$$\overline{M}_{out} = 1 - \delta/\delta_T \tag{3}$$

Figure 3 shows the predicted behavior for the physically meaningful range, $o < k < 1$.

Perhaps the most important result of the analysis is the expression for "pressing time" (t_p) listed above. It, in conjunction with the expression for m_L'', indicates that pressing time is proportional to the square of the web thickness (basis weight) and inversely proportional to applied air pressure and web liquid permeability (a strong function of compression level, moisture ratio, and freeness for a given pulp).

According to the model, there is no incentive to perform displacement pressing for times longer than t_p. The real challenge, then, is to minimize t_p, while maximizing m_L'' (the water available for displacement). This will require understanding and use of optimal operating strategies.

Experimental results. Actual experimental data, Fig. 4, show that significant water can be removed from an already well pressed web. For ingoing dryness levels in the 45% range, outgoing dryness levels of 65-68% have been achieved. Displacement time is a critical and positive variable up to about 50 ms; compressive pressure has only a modest positive effect, especially for short displacement times; the effectiveness of displacement pressing increases rapidly with freeness (permeability); and water removal is somewhat proportional to air pressure. As suggested by the model, basis weight has quite a strong negative effect on water removal.

For displacement pressing of fairly wet sheets, high levels of dryness can be achieved while retaining appreciable bulk, Fig. 5. The key is to compress the sheet just enough to keep it saturated, but not enough to hydraulically pressurize it. Air is then used to displace the water. This mode of pressing should be particularly advantageous for a number of grades where dryness and bulk are both desirable.

By taking advantage of a new driving force for dewatering, displacement pressing offers an added dimension in wet pressing. This may be used to produce much higher dryness levels (10-20 percentage points) with attendant savings in drying energy per unit of product, increased capacity, and improved runnability. Alternatively, displacement pressing may be used on relatively wet sheets to produce both dryness and bulkiness. The key is the displacement concept which overcomes the difficulty of creating a hydraulic pressure and allows the boundaries on traditional pressing practice to be pushed back.

DRYING

Cylinder Drying

McConnell (7) has concluded that almost 85% of all paper drying is carried out on cylinder dryers. These devices are simple and effective, and they provide a convenient sink for much of the low pressure steam available in an integrated mill. Unfortunately, however, they are limited to very low water removal rates and have almost no independent effect on paper properties. Low drying rates stem from the low temperature heat source, high thermal resistances between the heat source and the wet sheet from which water is being evaporated, the presence of air in the sheet requiring evaporation at the atmospheric boiling point, and vapor transport by diffusional flow under partial pressure gradients. The pressures and temperatures involved are sufficient to capture or set the density actually achieved in the press, but not to further improve properties. Hence, despite the efficacy and wide use of cylinder drying and recent improvements in the systems, significant further improvements are unlikely. Here again, new or more intense dewatering forces must be brought to bear to effect large gains. Impulse drying offers this potential.

Impulse Drying

Impulse drying is the name coined for the process of removing water from a moist web of paper in a high temperature press nip. Nip temperatures of 150-500°C, pressures from 0.3-7 MPa and nip residence times up to 100-150 ms usually bound the impulse drying regime. Physically, impulse drying encompasses some processes common to both pressing and drying, and some that are common to neither.

It is more appropriately called a water removal process, but impulse drying has "caught on" and will continue to be used.

First proposed by Wahren (8) in the late 1970's, impulse drying provides a dramatic example of a process involving new or more intense dewatering and densifying forces. Because of these forces, it offers major advantages in dewatering rates, energy use efficiency and property development. A subsequent paper will treat the performance of this process and quantify its advantages. The purpose of this section of this paper is to identify the driving forces generated during the impulse drying process.

Mechanisms in impulse drying. Figure 6 shows a schematic of a device for the laboratory study of impulse drying. It consists of a heated platen simulating the hot roll in a press nip and a plain opposing platen covered with a heat-resistant wet pressing felt. Either a falling-weight press simulator or the electrohydraulic press may be used to generate the desired pressure-time history. Because of its large thermal capacity, the temperature of the heated platen remains nearly constant over the short duration of a drying event. A typical pressure-time curve and the temperature-time histories at the sheet-felt interface for two different hot surface temperatures are shown in Fig. 7.

<u>Compression, heat, and mass transport processes</u>. Pressure and heat flux curves for impulse drying of a lightweight linerboard sheet are shown in Fig. 8. This lightly refined sheet was pressed to 40% solids before being impulse dried. Upon first contact with the hot surface, the moist sheet compresses as in wet pressing. For the given conditions, pressing of this sheet is likely to be compression controlled, requiring a high pressure for saturation. In the absence of all other effects, liquid saturation is estimated to occur at Point B.

In a simultaneous process, the high hot surface temperature and high contact pressure produce rapid sensible heating of the surface regions of the sheet. If the sheet is not saturated, boiling will begin when this region reaches the ambient saturation temperature, usually 212°F. Boiling is believed to begain at Point A, giving rise to the rapidly increasing heat flux beyond Point A through boiling heat transfer. Point A marks the end of the heatup period.

Boiling at or near the hot surface produces water vapor with a specific volume several hundred times that of the water evaporated. As this vapor flows into the still unsaturated sheet, it quickly reaches cooler sites where it condenses. Condensation raises the local temperature and degree of liquid saturation. Internal temperature data, Fig. 9, suggest that this process moves progressively through the sheet. At the same time, mechanical compression of the sheet promotes liquid saturation and reduces the distance between the hot surface and the boiling sites. The latter factor may account for the rising heat flux to Point C in Fig. 8. The combination of mechanical compression, liquid redistribution within the sheet, and vapor generation quickly fills the sheet and expels all air. Liquid removal by a vapor-induced displacement mechanism should follow. This may commence before the point of mechanical liquid saturation, Point B in Fig. 8. For faster pressure increases and lower surface temperatures, liquid dewatering induced by a hydraulic pressure gradient may precede vapor displacement of liquid. In either case, vapor-induced liquid dewatering continues until the mechanism is no longer functional or cannot be sustained by the external conditions. Under optimum conditions, from 40-50% of the total water in the sheet may be removed as liquid. This single mechanism, not operative in either pressing or conventional drying, is a significant contributor to the energy efficiency, rapid water removal and densifying potential provided by impulse drying.

Temperature measurements internal to the sheet, Fig. 9, show several important features. These temperatures rise much more rapidly than can be supported by a conduction heat transfer mechanism and quickly reach values much above the ambient boiling point through much of the sheet. This process continues until late in the drying cycle. Over this period, heat is transferred through the sheet by the evaporation-convection-condensation sequence described above, with evaporation near the hot surface and condensation in the lower, liquid-filled part of the sheet. Conduction probably dominates heat transfer from the hot surface to the immediate area. This process can account for rapid heatup and also for moisture redistribution in the sheet, known to occur from other tests.

Through this central part of the cycle, it appears that the upper part of the sheet is filled with vapor and that evaporation continues to sustain the heat transfer required by the progressive heatup of the sheet. Based on the temperatures measured in the sheet, vapor pressure well above one atmosphere, but decreasing through the vapor region, are generated.

Assuming a saturation vapor pressure corresponding to a measured temperature, the maximum internal sheet pressure is 1.4 MPa near the hot surface, failling to near zero lower in the sheet. This substantial vapor pressure gradient is believed to induce a strong bulk vapor flow, giving rise to displacement of the water in the lower part of the sheet and supporting the evaporation-condensation sequence cited above. It is also believed to prevent any significant capillary flow of liquid back to the hot surface. Much or even all of the liquid dewatering may be driven by this mechanism, although some hydraulically induced liquid dewatering may occur early in the cycle, as noted above. Chemical tracers have been used to show that as much as 40-50% of the total water removal may occur as liquid transport.

Near the end of the cycle, the upper sheet temperatures drop rapidly, whereas the lower temperatures continue to rise, Fig. 9. This transition is believed to occur when the transverse compressive pressure can no longer sustain the vapor pressure. Reduced heat flux from progressive drying near the hot surface and lower contact pressures may contribute to the temperature drop, as well. Continued heating of the lower regions is likely the result of continued condensation of low pressure vapor in this region and conduction from the upper hotter regions. There may be appreciable flashing of supersaturated liquid remaining in the sheet as the pressure is reduced. This mechanism may actually account for significant water removal.

In summary, the first few milliseconds of an impulse drying event are dominated by mechanical compression and sensible heating of the web surface region. Preheating the web can shorten this period. Water removal in this period, if it occurs at all, is predominantly by a wet pressing mechanism. This is followed by a fairly long period of intense heat transfer to the web, evaporation and condensation to rapidly heat the interior of the web and redistribute moisture, and intense vapor pressurization of the web to support the high heat flux levels and displace liquid water from the sheet. Liquid displacement by vapor flow is the predominant water removal mechanism in this period. Late in the cycle, heat flux levels decline because of drying near the hot surface and reduced contact pressure. Internal temperatures near the hot surface drop because the high vapor pressures needed to sustain them exceed the available compressive pressure. Hot liquid in some regions of the sheet flashes as the pressure is dropped. Vapor flow from the sheet dominates water removal during this period. These processes seem to account for the bulk of the heat and mass transfer within and out of the sheet. All of these events occur over a period of only a few milliseconds.

Density development. The intensity of the physical processes occurring during impulse drying causes considerable densification of the wet web, even for a small amount of total water removal. Local density measurements, made over three thickness regions of the sheet, shown in Fig. 10, illustrate this point. To describe the densification process, it is convenient to divide the nip residence period into three time intervals numbered 1-3. In interval 1, the sheet density develops purely as a result of mechanical compression as it would in wet pressing. Densities throughout the sheet are uniform during this period. Liquid water may be removed from the sheet during this period. The wet pressing effect may be augmented slightly by "softening" of the fiber network and reduced water viscosity, both resulting from elevated temperatures. These effects are probably slight, especially for very short nips.

Shortly into interval 2, the two lower regions (75% of the sheet) reach a maximum density and then begin to expand. Flow resistance in these regions is believed to limit the structural pressure over this interval and cause the resulting downturn in density. Intense dewatering driven by the high vapor pressure in the upper region causes a structural pressure gradient giving rise to a higher density in the lowest region. Near the hot surface the growing vapor pressure supports the externally applied pressure and prevents further densification, leading to a nearly constant density of this upper region over the central part of the event.

Late in the event in interval 3, the external pressure drops and the internal vapor pressure follows, as noted above. This gives rise to a rapid collapse and densification of the previously vapor-filled upper region of the sheet. Progressive drying of the region near the hot surface also occurs. As a consequence, this region achieves a very high density level. Overall, the sheet becomes somewhat bulky in the center, a bit more dense at the flow exiting surface and very dense near the hot surface. The degree to which this J-shaped profile develops depends strongly on the impulse drying conditions. Even modest water removal by impulse drying produces significantly higher average densities and the J-shaped profile, as compared to conventional processing. Generally, these differences increase directly as more water is removed by impulse drying. Finally, as the sheet is dewatered and densified, it is almost totally restrained, effectively preventing shrinkage.

New dewatering and densifying forces. Earlier in this paper it was noted that significant improvement in pressing and drying performance would require new or more intense mechanisms than those typically employed. Impulse drying epitomizes this concept by offering at least the following driving forces:

1. Heat addition rates several orders of magnitude higher than those in conventional drying. These are produced by much higher surface temperatures, higher contact pressures and boiling heat transfer in an air-free environment.
2. Transverse compressive stresses typical of intense wet pressing, never before used in the post-pressing solids range. These provide additional mechanical dewatering, good thermal contact for effective heat transfer, web consolidation during drying for density development, and lateral restraint during drying for property development.
3. Rapid heat transfer within the sheet via an evaporation-convection-condensation sequence in an air-free environment. This accommodates the extremely high surface heat transfer

rates and provides rapid internal heating and moisture redistribution.

4. Large total pressure gradients within the sheet drive the evaporation-condensation process by producing strong bulk flow of vapor within the sheet. This, in turn, displaces liquid water from the sheet. Fluid pressure forces within the sheet, generated and sustained by the total vapor pressure, are partly responsible for development of the unusual sheet density profile. The collapse of the vapor pressure near the end of the cycle allows rapid densification of the upper regions of the sheet and promotes rapid vapor phase water removal via flashing of supersaturated hot water.

General performance characteristics. Impulse drying is a hybrid pressing and drying process. By generating the intense forces described above, impulse drying can produce the following performance characteristics:

1. Water removal rates of the order of 5000 kg/hr/m^2. Drying rates in cylinder drying are about 20-25 kg/hr/m^2. Rate depends strongly on hot surface temperature, ingoing moisture ratio, nip residence time and pressure. For perspective, a newsprint sheet at 50% solids can be dewatered to 90% solids in about 20 ms.
2. Specific energy use levels of around 1100 kJ/kg of water removed for sheets preheated to 100°C. Impulse drying of room temperature sheets requires somewhat more energy because of the necessary

sensible heating and a lower overall efficiency. Conventional cylinder drying uses about 3500-4500 kJ/kg of water removed.

3. Sheet density increases of 50% or more depending on how much water is removed by impulse drying. Densities produced by impulse drying are equivalent to those produced by wet pressing in terms of strength development. Strongly J or U shaped density profiles result from impulse drying on one or two sides, respectively.
4. Much smoother, more closed, more pick resistant and less absorbent surfaces. These seem to all result from the extreme densification next to the hot surface. Optical properties are little changed by impulse drying.

Overall, impulse drying has the potential to allow much smaller drying equipment (perhaps by 100:1), the use of much less energy but of a higher grade, and the opportunity to dramatically influence paper properties. Paper property development and control, especially with low cost furnishes, may be the most important advantage.

CONCLUDING COMMENTS

Two new dewatering and web consolidation processes have been described; displacement pressing and impulse drying. Each takes advantage of new or augmented forces to produce dramatic and important improvements in performance. Improvement and control of final sheet properties are likely to be the most important advantages of each process. Increases in productivity and reductions in energy consumption may also be important. These processes illustrate that new mechanisms can be used to move outside the boundaries of conventional system performance. Both processes are now undergoing laboratory evaluation and development.

Impulse drying is sufficiently developed to have demonstrated all of the benefits cited in bench scale studies. A large project, supported by the U.S. Department of Energy, is well along in developing the data base for commercial application. Further laboratory work on displacement pressing should determine the engineering and economic feasibility of this process in the near future.

ACKNOWLEDGMENTS

The work reported in this paper was supported by the members of The Institute of Paper Chemistry. Excellent experimental help was provided by James Loughran and Lester Nett. Some of the early exploratory work was directed by Dr. Fred Ahrens, who is no longer at the Institute. All of these sources of support and help are gratefully acknowledged.

REFERENCES

1. Busker, L. H., Tappi 54(3):373(1971).

2. Busker, L. H., and Cronin, D. C., Preprints of the International Water Removal Symposium, Vancouver, 1982. p. 25.

3. Wicks, L., Tappi 66(4):61-64(1983).

4. MacLaurin, D. J., and Whalen, J. F., Tappi 37(12):608(1954).

5. Heller, H. H., et al., Tappi 55(6):893-6(1972).

6. Zotterman, C., and Wahren, D., Paper Trade J. 162(16):37, 64(1978).

7. McConnell, R. R., The Institute of Paper Chemistry, Project 3394, Report One, Feb., 1980.

8. Wahren, D., U.S. pat. 4,324,613(April 13, 1982).

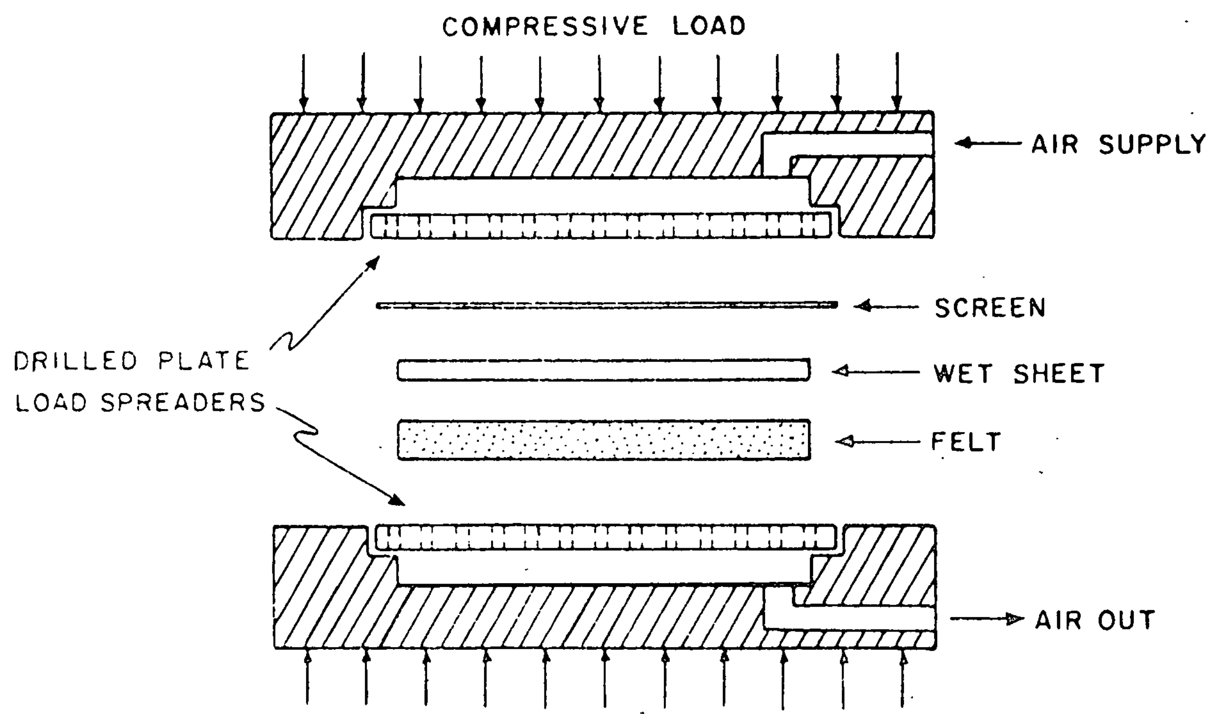


Figure 1. Displacement pressing chamber schematic.

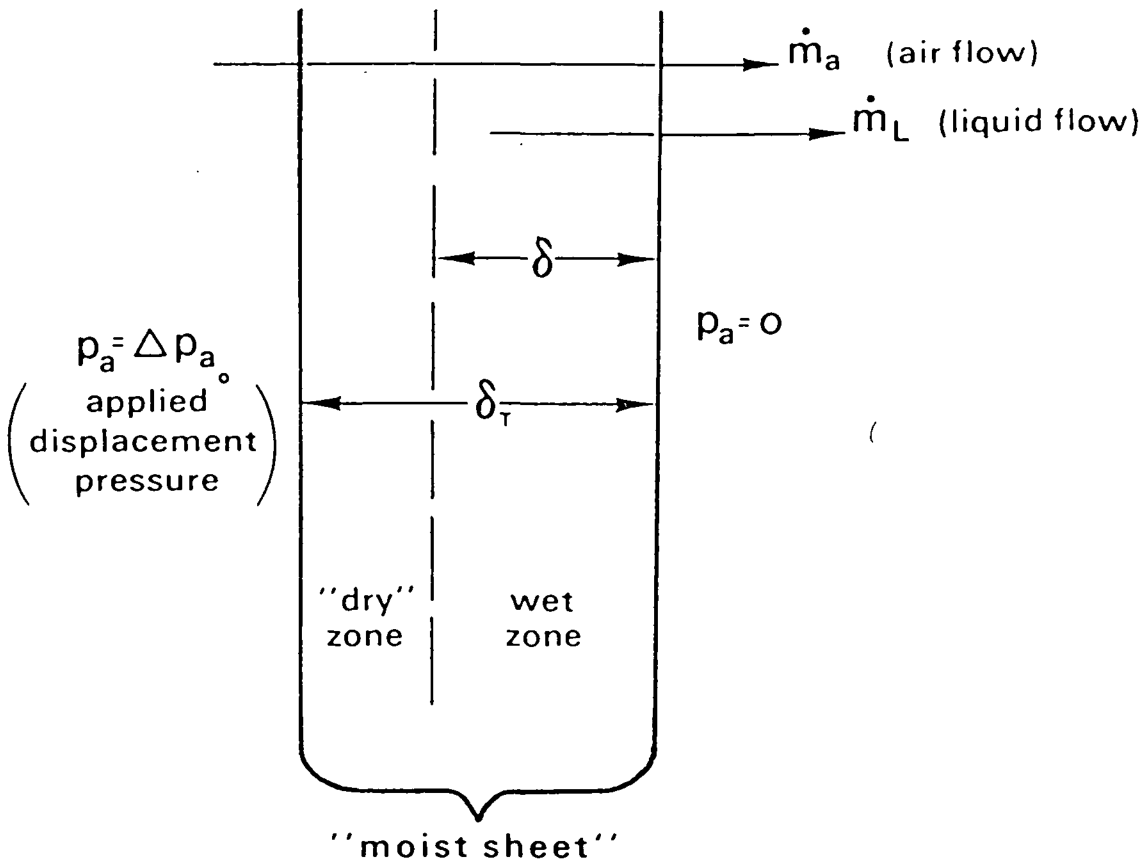


Figure 2. Two-zone model of displacement pressing.

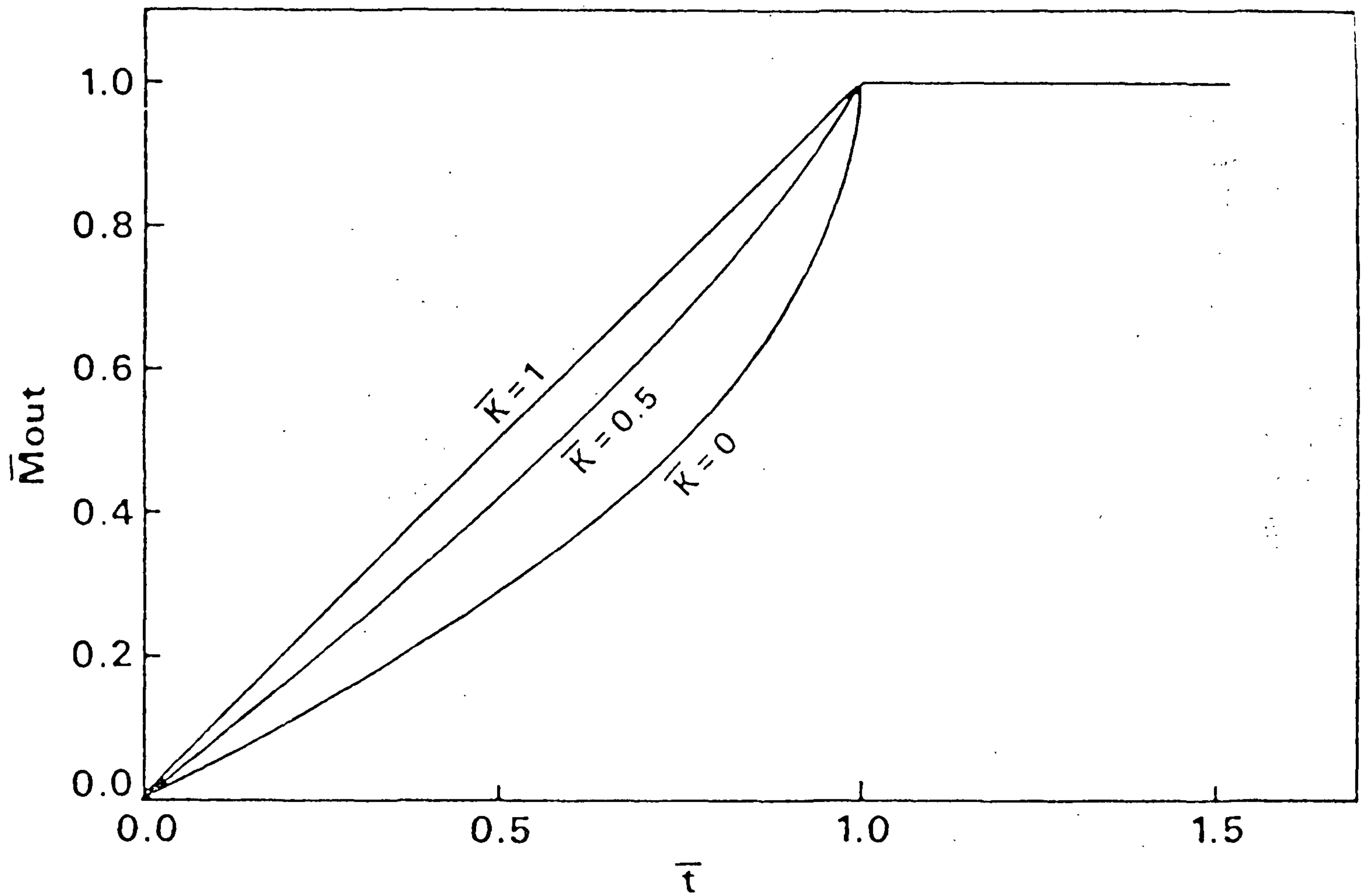


Figure 3. Cumulative moisture removal as a function of dimensionless time, as predicted by the two-zone model.

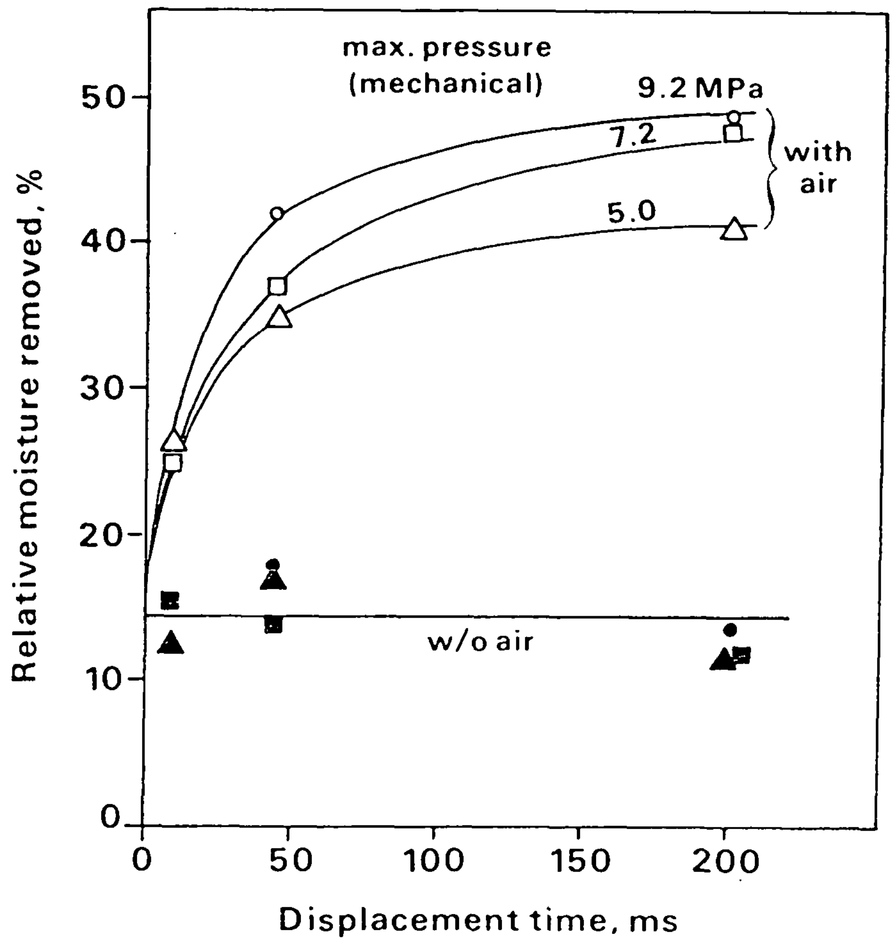


Figure 4. Results of displacement pressing of 63 g/m^2 handsheets of once-dried bleached softwood kraft pulp at 720 mL CSF. Initial dryness - 43-45%.

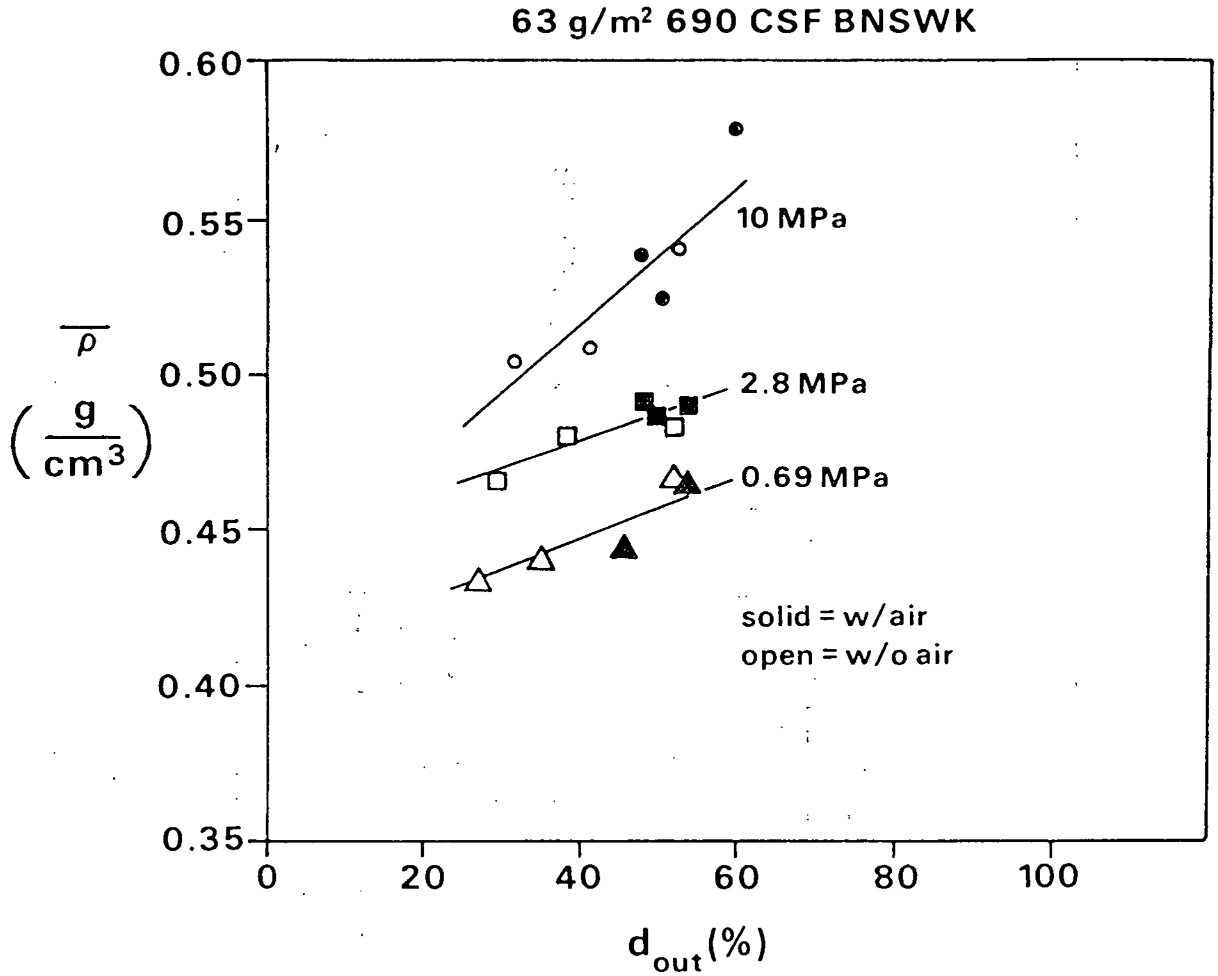


Figure 5. Dryness gains and bulk retention in displacement pressing for various pressing pressures.

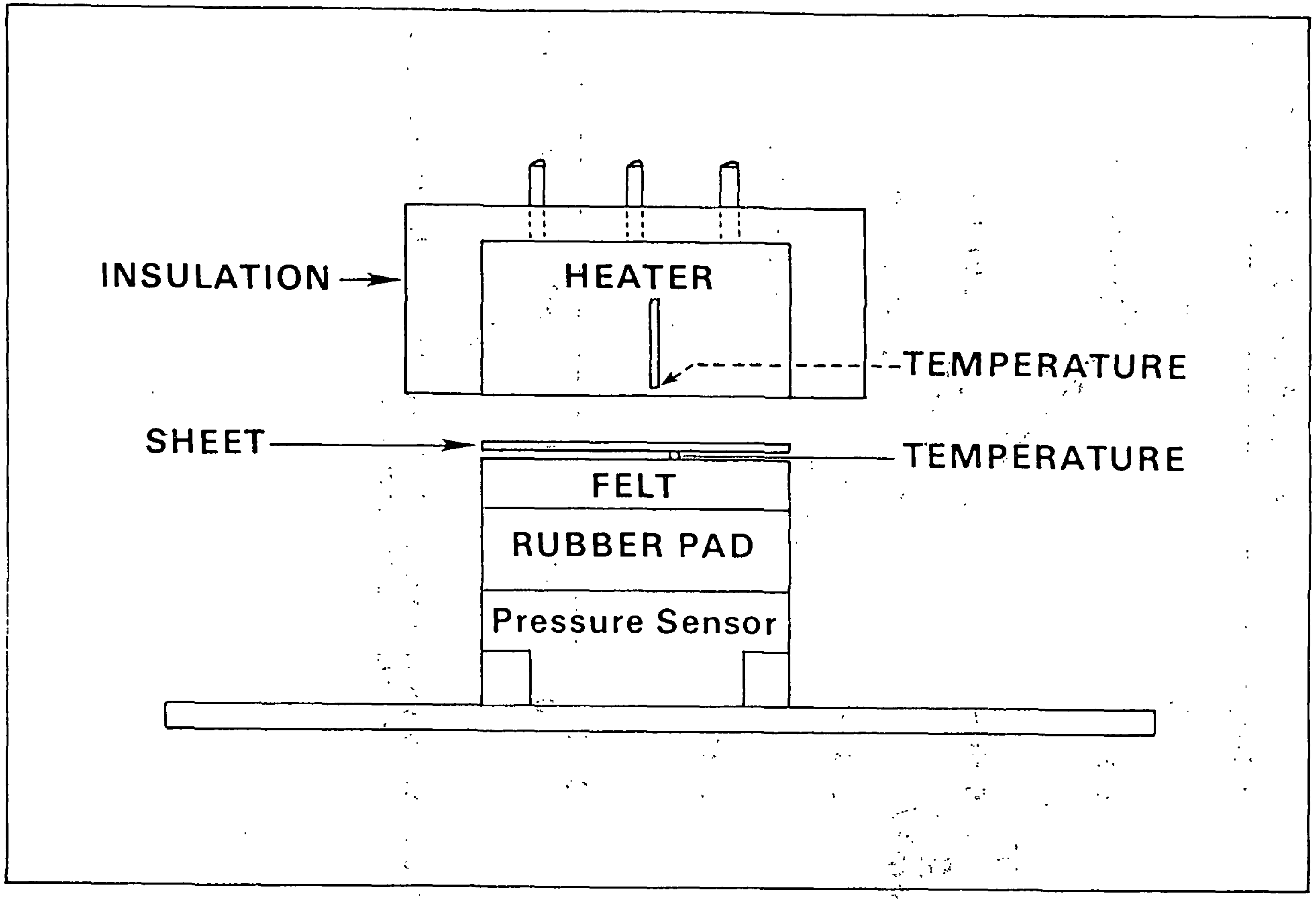


Figure 6. Schematic of an impulse drying head for use in a laboratory wet press simulator.

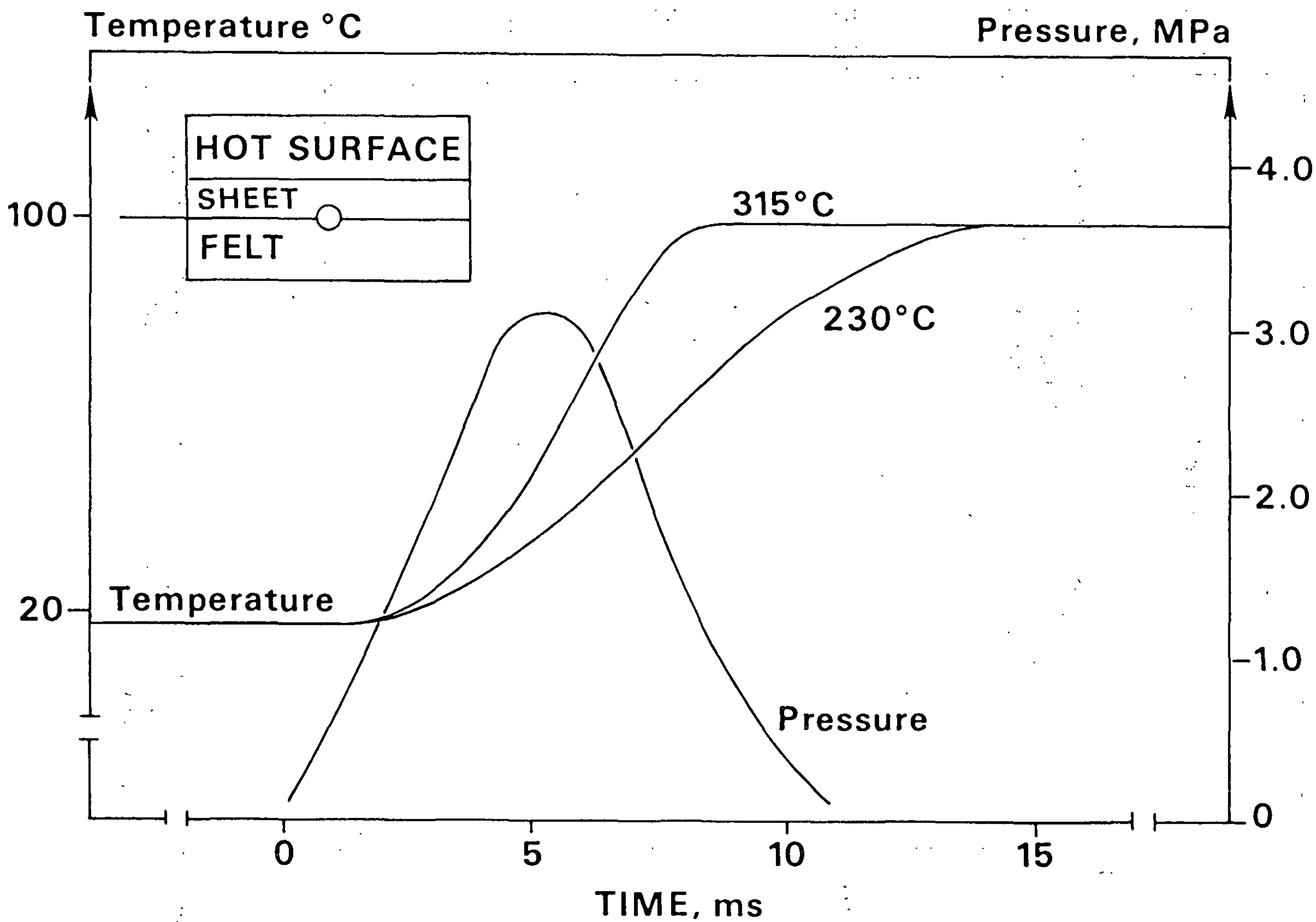


Figure 7. Typical recordings of total nip pressure and sheet/felt interface temperature for impulse drying at two hot surface temperatures.

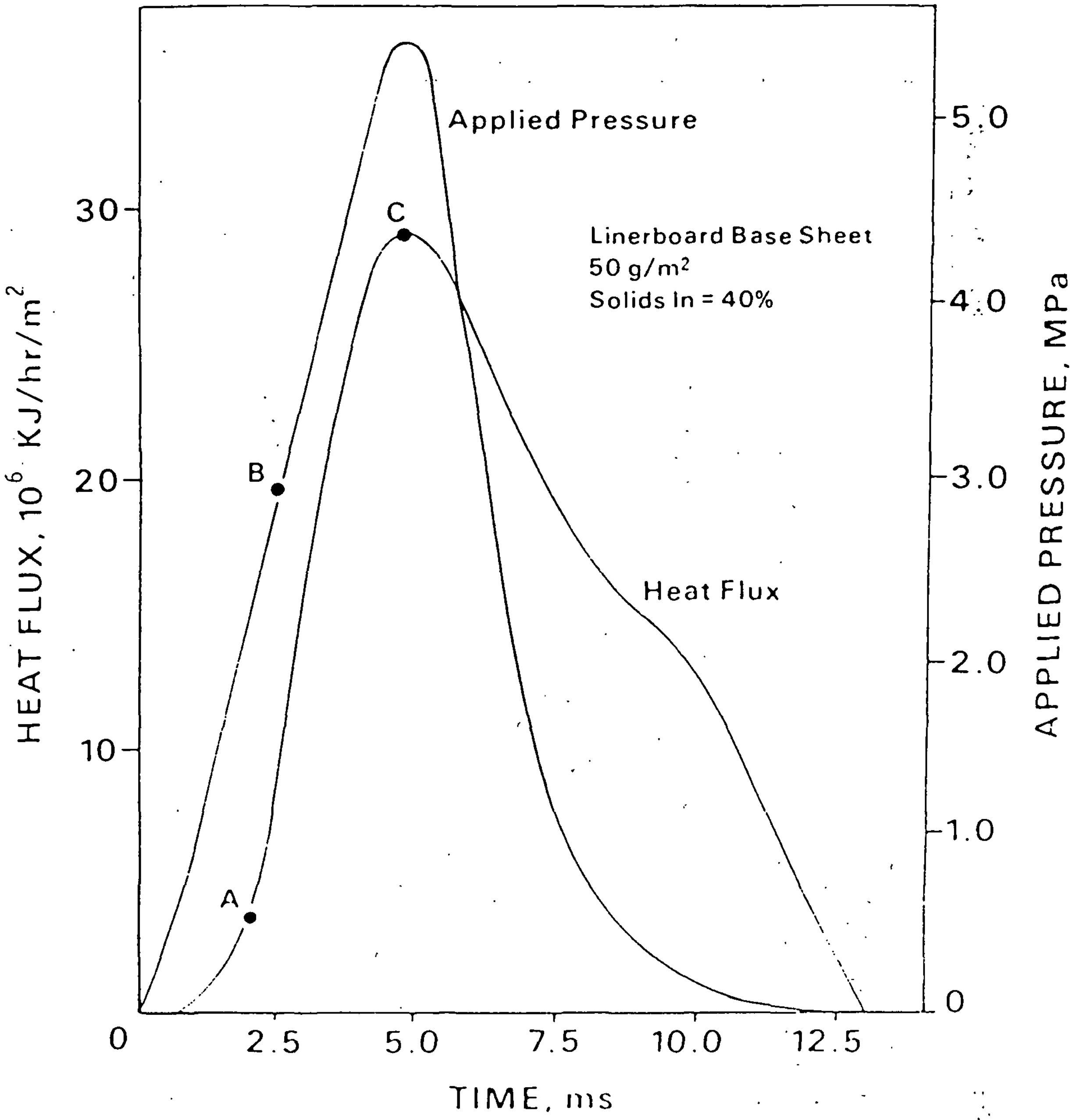


Figure 8. Typical recordings of instantaneous applied pressure and heat flux for impulse drying of a room temperature web. Hot surface temperature = 315°C.

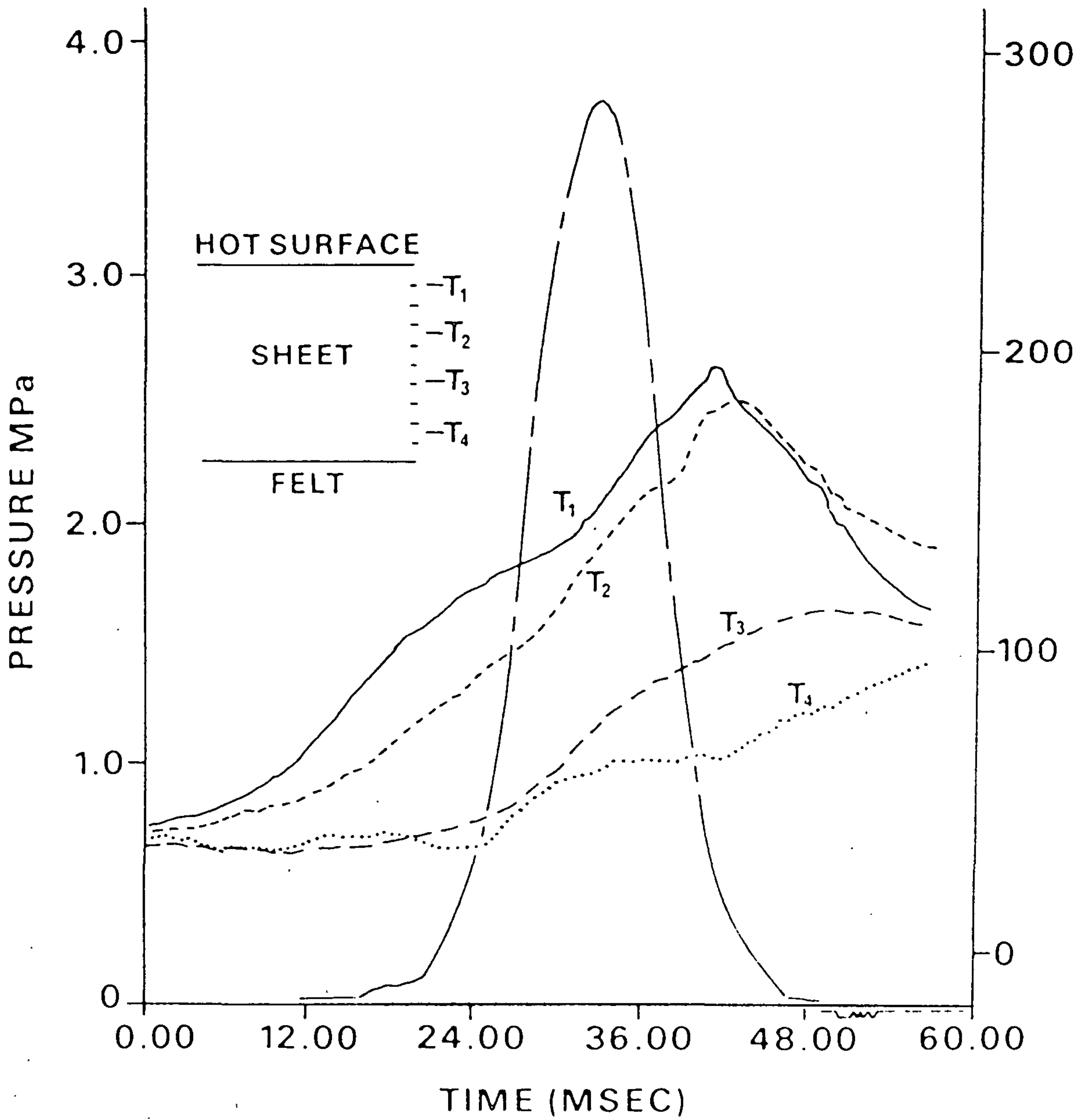


Figure 9. Applied pressure and internal sheet temperatures for impulse drying of a fines free unbleached softwood kraft sheet. Basis weight = 100 g/m^2. Hot surface temperature = 315°C. Initial moisture content = 60%.

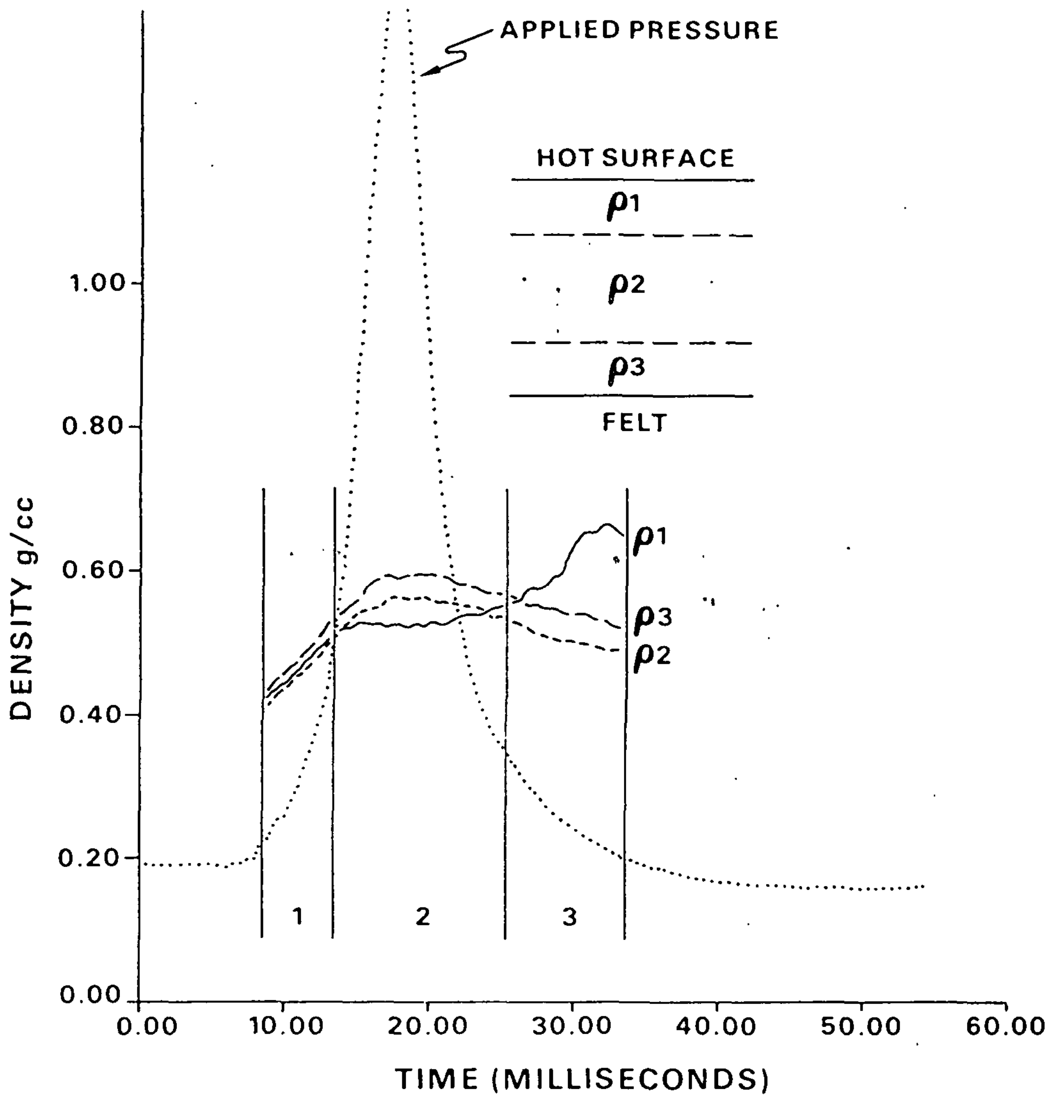


Figure 10. Applied pressure and regional densities for impulse drying of a fines free unbleached softwood kraft sheet. Basis weight = 173 g/m^2. Hot surface temperature = 315°C. Initial moisture content = 58%.

IPC TECHNICAL PAPER SERIES #176

GEORGIA-PACIFIC
CORPORATION
ATLANTA, GEORGIA